

In-flight Performance Evaluation of the Deep Space 1 Autonomous Navigation System

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NASA's New Millennium Program consists of a series of missions whose primary purpose is to demonstrate the feasibility of new technologies for spaceflight. Deep Space 1 is the first in this series of missions. It was launched on October 24, 1999 and has completed its first leg of the mission -- flyby of the asteroid Braille -- on July 29, 1999. Additional encounters are planned with the transition object Wilson-Harrington in January 2001 and with the short period comet Borrelly in September 2001. The new technologies being demonstrated on DS1 include, among others, an ion propulsion system to provide maneuvering thrust, a combined visible/infrared/ultraviolet imaging instrument named MICAS (Miniature Integrated Camera and Spectrometer), and an autonomous navigation system. The purpose of this paper is to describe the computational elements of the autonomous navigation system and assess its performance in guiding the spacecraft to its first target. Some of the difficulties encountered during this leg, and how they were overcome, will also be described.

The onboard navigation system, in order to be as self-contained as possible, uses images of asteroids taken by the MICAS camera as its sole data type in determining the spacecraft's trajectory. The basic premise is very simple -- triangulation of the spacecraft's position by sighting two or more asteroids. These observations are incorporated into a least-squares filter to estimate, in addition to the spacecraft's position, its velocity and other dynamic parameters which affect the trajectory. Once the orbit is determined, maneuvers can be planned and executed to achieve a desired target. The computational elements of the navigation system then can be divided into three distinct elements: the image processing to locate the centroid of the beacon asteroid and surrounding guide stars in the image, orbit determination, and maneuver planning. A fourth element, termed RSEN (Reduced State Encounter Navigation), was also used during the final approach to the target to provide rapid navigation updates needed to track the asteroid during flyby. Prior to launch, all these elements except RSEN were tested using simulated data, and the results indicated that the system was capable of determining the spacecraft's position and velocity to accuracies of approximately 100 km and 0.2 m/s (1 sigma), respectively, during the cruise portion of the trajectory. During final approach when the target itself is sighted, the position fix improves to about 1.5 km (1 sigma), sufficient to meet the planned 9 km flyby altitude requirement.

Two weeks after launch, a major hurdle was encountered when the first images taken by MICAS were returned to the ground. It was found that the images were substantially corrupted by stray light which had leaked into the camera optics. Consequently, a major redesign of the image processing element was undertaken to be able to handle images corrupted by stray light -- a process which was not completed and loaded onto the spacecraft until mid February of 1999.

Once this new software was uploaded, the first onboard use of the navigation compute elements was performed on February 18, 1999, with the software processing images from 4 beacon asteroids. After three more such campaigns on February 22, March 1, and March 8, the spacecraft computed its first completely autonomous solution on March 8. Comparison of this solution with ephemeris information obtained from standard radiometric tracking data processed on the ground indicated that the solution had a position accuracy of about 6000 km and a velocity accuracy of 5 m/s. Although this was sufficient for normal cruise operations, it was far worse than preflight predictions. The cause for the large errors was twofold: first, the camera turned out to be less sensitive than its design resulting in loss of signal for dimmer asteroids, and second, the camera optics had distortions which were not correctable by our standard distortion models. The first problem was handled by more judicious selection of beacon; the second required another software redesign. In early June, a second software upload was performed which had higher order distortion models for the camera, as well as the first load of the RSEN tracking code. Meanwhile, the spacecraft continued its onboard solutions, whose accuracy ranged from 5000 to 20,000 km depending on the availability of suitably bright targets and where the centroids fell in the distorted image field.

By late June, the upgrades to the software improved the onboard orbit determination accuracies to better than 1000 km in position and less than 0.5 m/s in velocity, and they stayed in the 500-1000 km and 0.2-0.5 m/s level for the remainder of the cruise to Braille. This still was a factor of 2 or 3 larger than preflight estimates, partially due to the limited number of brighter asteroids available, but also attributable to biases in the centroids of between 0.5 and 1.0 pixels which are still unexplained. Nevertheless, by mid-July, the cruise portion of the autonomous navigation system was deemed to be validated and, following encounter, has been used with little ground intervention as of this writing.

The asteroid approach phase of the mission posed special problems for navigation due to the small size and dimness of Braille. Because of this, image processing and orbit determination were performed on the ground from images downlinked from the spacecraft. The first detection of Braille occurred just 2.5 days prior to encounter (E), and showed that the ground-based Braille ephemeris was over 300 km in error. The spacecraft therefore performed a maneuver at E-1 day to retarget its course for a 15 km radius flyby. Additional images taken between E-1 day and E-18 hours pinpointed the post-maneuver flyby radius to about 6 km with an uncertainty of 10 km (1 sigma), so a final targeting maneuver at E-6 hours was planned and executed. Post-encounter reconstruction of the trajectory showed that the actual flyby radius was 28 km.

The RSEN tracking code unfortunately failed to keep Braille in the camera FOV in the minutes surrounding encounter. The reason for this was that the brightness of Braille in the APS was far too low to be detected due to a combination of poor lighting geometry, peculiarities in the sensitivity of the camera, and Braille's albedo being lower than anticipated. Post-encounter analysis showed however, that if the more sensitive CCD detector had been used, RSEN could have spotted Braille in the frame and properly tracked it during flyby. As a lesson learned for future flybys, more attention will be given to correctly modeling the brightness of the targets in the camera frame.